Ring around a Stellar Shell: A Tale of Scientific Serendipity

USING a three-dimensional (3D) model run on some of the fastest computers in the world, Laboratory astrophysicists have cracked a mystery of stellar evolution that has puzzled the astronomical community for nearly four decades. For years, physicists and astronomers theorized that low-mass stars (one to two times the mass of our Sun) produce great amounts of the helium-3 isotope. According to this theory, as these stars evolve, they eventually exhaust the hydrogen in their cores before violently igniting their helium-rich cores in a "helium flash."

That process, carried out by billions of stars over billions of years, should have resulted in an interstellar medium enriched with the light helium-3 isotope, adding to the helium-3 created during the big bang. Accepted calculations indicate that the big bang produced mostly hydrogen, mixed with about 0.001 percent helium-3 and 4 percent helium-4. Later, low-mass stars should have increased the helium-3 amount in the interstellar medium to 0.1 percent. But observations show that it remains at 0.001 percent, raising the question of where is the missing helium-3?

Using Djehuty, a Livermore-developed 3D astrophysics code, Laboratory scientists Peter Eggleton and David Dearborn uncovered a mixing mechanism that not only accounts for the mysteriously missing helium-3, but also could explain an equally mysterious overabundance of carbon-13. Eggleton and Dearborn's discovery came out of a 3D-simulation study, supported in part by the Laboratory Directed and Research Development Program, exploring the helium flashes that occur when a low-mass star evolves into a red giant.

Flash Leads to Insight

A star that has a total mass equal to or less than the Sun will burn hydrogen at its core for nearly 10 billion years, turning that hydrogen into various isotopes of helium. When the hydrogen supply is exhausted, the core contracts, raising the star's temperature and density to the point where the core begins to burn helium. This dense core, where the nuclear burning takes place, is surrounded by a large, low-mass convective envelope that is a mixture of hydrogen and the "missing" helium-3.

"In a helium flash, the star's core ignites under high densities and temperatures," explains Eggleton. "This ignition leads to more nuclear reactions in the core as the helium rapidly converts to carbon." Most one-dimensional (1D) and two-dimensional (2D) simulations show that these reactions are plentiful and rapid enough to be explosive. "However," says Eggleton, "the fact we observe stars that have passed through helium flashes indicates a flash is not extremely violent."

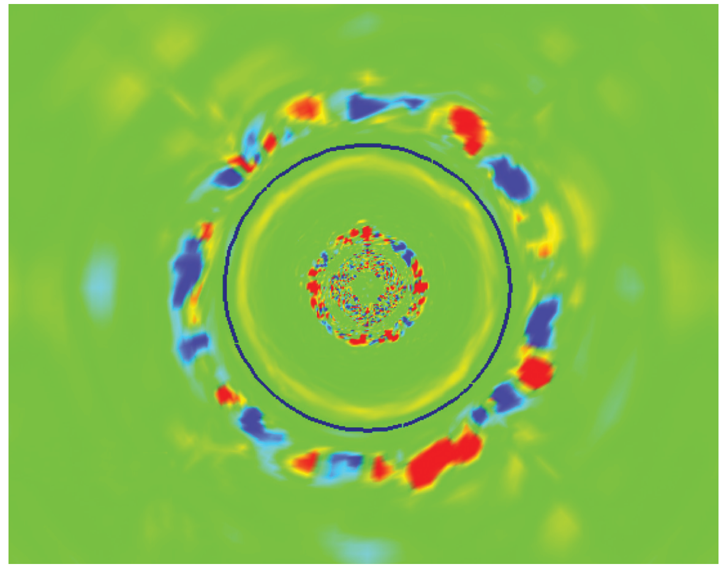
> ***The most exciting phrase to hear in science, the one that heralds new discoveries, is not "Eureka!" but "That's funny."***
>
> ***—Isaac Asimov***

Eggleton, Dearborn, and John Lattanzio from Australia's Monash University decided the helium flash would be a good test problem for Djehuty, which simulates the evolution and structure of stars. Djehuty is designed for 3D stellar modeling on massively parallel supercomputers. (See *S&TR,* May 2002, pp. 4–10.)

In general, astrophysicists depend on 1D and 2D codes for much of their stellar modeling. "Because a star is often assumed to be a sphere, what happens in one dimension along the radius should apply in all directions," explains Dearborn. "For some conditions, that assumption holds. However, for unstable conditions in which material mixing occurs, we need a 3D code for our simulations."

"When we looked at the helium flash evolving in three dimensions, we expected the simulation to show what has been

During their evolution, low-mass stars enrich the interstellar medium with elements, creating a planetary nebula such as the one shown here. (Image courtesy of the Space Telescope Science Institute.)



A three-dimensional model of a helium flash is shown in this two-dimensional cross section. The solid, dark-blue ring is the hydrogen-burning shell. Turbulent motion occurs in the helium-burning core near the center, as expected. The unexpected ring of turbulence just outside the hydrogen shell is the result of helium-3 burning.

observed: rapid expansion but no explosion," says Eggleton. They ran the helium-flash simulation using up to 10 million mesh points with time steps corresponding to one-tenth of a second. The simulation ran on 351 processors and modeled reactions occurring over 10,000 seconds, which translates to modeling a little more than 2.5 hours in the life of a red giant star. This simulation took a few days to run on the Laboratory's supercomputers.

While examining the results of the simulation—which did, indeed, show a rapid expansion with no explosion—Dearborn noticed something strange. "We saw an unexpected shell of matter deep inside the star, just outside the hydrogen-burning layer on top of the helium core," says Dearborn. "None of our 1D or 2D models has shown this ring."

"When he pointed the shell out, it was an 'ah-ha' moment for us both," notes Eggleton. The shell is evidence of a molecular-weight inversion—a thin layer of helium-3—surrounding a lighter weight hydrogen layer. "This inversion set up a classic Rayleigh–Taylor situation," explains Eggleton, "similar to trying to float water on top of oil. The heavier material on top of a lighter material created a very unstable situation. In a 2D or 3D simulation, we would expect the heavier elements to be driven to the core by the enormous pull of the star's gravity—but that's not what the simulation revealed."

The 3D simulation showed that the burning shell of helium-3, just outside the lighter weight hydrogen layer, created a turbulent mixing motion, much like a stellar lava lamp. During this mixing process, bubbles of material substantially depleted in helium-3 float toward the surface of the star. Helium-3-enriched material from above the thin shell moves in the opposite direction, sinking farther into the core and then burning. In this reaction, two helium-3 atoms form a single helium-4 atom and two protons. Thus, the rapid mixing process effectively destroys helium-3 in the star, explaining why so little of this isotope appears in the material ejected during a helium flash. This mixing and burning process occurs on a very short time scale for stellar evolution: in a few hundred to a thousand years, compared with the tens to hundreds of millions of years it takes for a star with the mass of the Sun to evolve into a red giant.

The Carbon-13 Conundrum

The deep mixing that occurs inside low-mass stars as they evolve into red giants could also solve another astrophysical puzzle: the question of why so much carbon-13 is observed in these stars. "According to earlier theoretical models," says Eggleton, "old, low-mass stars during their evolution into red giants should have increased amounts of carbon-13 in their spectra, on the order of two to three times more. Yet, observations show that carbon-13 in these stars is commonly enriched by a factor of 10 to 20. This incongruity has perplexed scientists since it was first observed."

Deep mixing uncovered in the Djehuty simulation offers an explanation for the discrepancy between theory and observation. When large reservoirs of burnt helium-3 (that is, protons and alpha particles) bubble upward and mix with the carbon-12 in the convective envelope, carbon-12 is mixed downward to the hot helium-3-burning layer. In this layer, the carbon-12 can be burned to carbon-13 and then mixed upward again. Eggleton says, "This deep mixing thus not only accounts for the 'missing' helium-3 but also could account for the overabundance of carbon-13. In a way, Djehuty has allowed us to deal a blow to two odd birds with a single stone."

Robert Kraft, University of California (UC) at Santa Cruz professor emeritus and an expert in stellar abundances and evolution, agrees that the Djehuty 3D stellar modeling may help solve the carbon-13 mystery. "Many researchers are specifically looking at the stellar abundances of carbon-12 compared to carbon-13," he explains. "Spectral observations are ongoing at the largest telescopes in the world, including UC's Lick telescope, the 10-meter Keck telescope in Hawaii, and the European Southern telescope in Chile. We know from these observations that more carbon-13 exists than can be accounted for. The 3D modeling achievable with Djehuty may clear up this mystery."

Power of Three Dimensions

Moving forward from this serendipitous discovery, Eggleton plans to tackle other thorny issues with Djehuty. His current project involves examining surface convection in low-mass stars. "With the resolution available on Livermore's supercomputers, Djehuty can model the convection of a low-mass star but not of a star such as our Sun," says Eggleton. "The Sun has a narrow but intense convection layer near the surface, requiring a much higher resolution." Modeling the Sun's convection layer would require a minimum of a hundred billion mesh points. Low-mass stars with their more spread-out convection layers require a billion mesh points, an amount achievable on Livermore's supercomputers. "We'll 'see' into the surface layers using Djehuty," says Eggleton. "We can transfer this information to our 1D codes, which are much faster and require less computer power than the 3D Djehuty code. The end result will be more accurate 1D codes."

Other projects Eggleton hopes to explore with Djehuty include investigating core convection in massive stars, with and without rotation; surface convection in a binary system of evolved red giants, where two stars are so close that they share a common surface layer but have separate cores; and various types of supernova explosions. "Who knows what wonderful discoveries we might find along the way," says Eggleton.

—Ann Parker

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